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An Aquatic Environment Assessment Model for the Comprehensive Assessment of Environmental Measures in Metropolitan Areas

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ABSTRACT: We have developed simulation models that describe the effects that urban environmental measures have on urban activities such as transportation and land use, and evaluate them from the perspective of the environment, quality of life, and the economy. This paper presents an aquatic environment assessment model that may be added to the above-mentioned simulation models, and presents the results of a case-study of the Sendai metropolitan area. The results confirmed that the aquatic environment assessment model is reproducible, with sufficient accuracy in assessing the aquatic environment. The case-study assessed the impact that land use measures, sewer planning, and water quality planning had on the environment, and made clear their effect on watershed retention capacity and the water quality improvement index.

Keywords: Aquatic environment, Environmental load, Assessment model, Water quality

1. INTRODUCTION

Environmental considerations in urban planning tend to focus on measures to counter global warming, and relatively few measures focus on such environmental elements as the aquatic environment, the thermal environment, plants and animals, and the ecosystem. In particular, there are but few examples of city structure and land use reviews that consider the effects on the aquatic environment at the planning stage, even though their effect on the aquatic environment is significant.

The authors have developed a comprehensive urban environment simulation model system that describes the effects that urban environmental measures have on urban activities such as transportation and land use, and evaluates them from the perspective of the environment, quality of life, and the economy. This paper presents an aquatic environment assessment model that forms one part of the model system. The goal of this paper is twofold.

1)The previously-developed model system is limited to evaluations of air pollution (air quality and noise), and the global environment (greenhouse gases); this paper creates and adds to the model system an aquatic environment assessment model with a strong connection to city structure and land use.

2) Second, this paper conducts an aquatic environment assessment case-study of the Natori and Hirose River areas in the Sendai metropolitan area, considering land use measures, the sewage planning, and water resource planning.

2. CHARACTERISTICS OF THIS STUDY

2.1 Review of Prior Study

Comprehensive models that combine land use and transportation models with environmental assessment models have been published by RURBAN[1], PROPLIS[2], and MERS[3][4]. These models combine land use and transportation models with environmental assessment models such as atmospheric diffusion and noise level forecasting, and calculate various indexes including CO_2 and NO_x emissions, exposure levels of NO_2 and PM, and noise pollution.

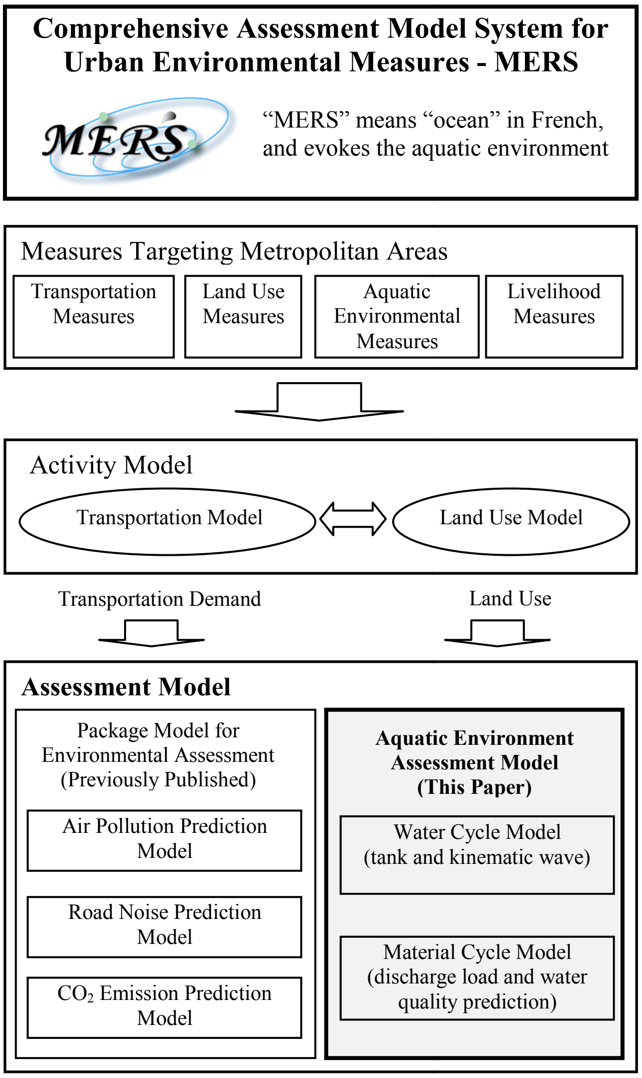
PROPOLIS and MERS have continued their efforts to make an even greater number environmental assessment possible, but have yet to assess the recent planning issues of the aquatic environment, the thermal environment, and biodiversity.

At the International Water Association ("IWA"), future cities seen from the aquatic environment have become a major subject of study [5]. The National Institute for Environmental Studies [6], Okugawa*et al* [7], and Tsujikura*et al*[8] each have models like the one we seek to develop here, which considers both the water cycle and material cycle. The merits of these models are that they recreate the phenomenon in detail, and make possible environmental assessments that display a high degree of accuracy. The demerits, however, are that they are not linked to land use or transportation models.

There is software available for assessing policies that address aquatic environments and target cities. For example, MIKE URBAN's software [9] can assess a city's aquatic environmental measures, predict floods, and visually display the results of the assessment using GIS, but it does not include land use or transportation models.

2.2 Characteristics of this Study

The first characteristic of this study is that it adds, for the first time, the aquatic environment to the evaluation index of a comprehensive model that combines land use and



note: "quality of life assessment model" and "economic assessment model" are omitted.

Figure 1: Structure of the Model System

transportation models with environmental assessment models.Land use expresses the change in population distribution due to transportation services, as well as land uses such as buildings, agriculture, and forests.

The second characteristic of this study is that it links land use and transportation models to water cycle and material cycle models, seeking not to refine the models of earlier study, but rather to use them as elements of this study.

The Model System, which incorporates the above characteristics, is displayed in Figure 1. It takes MERS, a previously developed model, and adds to it a model that makes it possible to evaluate the aquatic environment including the volume and quality of water in city rivers. The aquatic environmental assessment model makes it possible to evaluate the effect that changes in land use have on the water cycle and material cycle.

3. CONSTRUCTINGTHEAQUATIC ENVIRONMENTALASSESSMENTMODEL

3.1 Model Structure

The aquatic environmental assessment model is composed

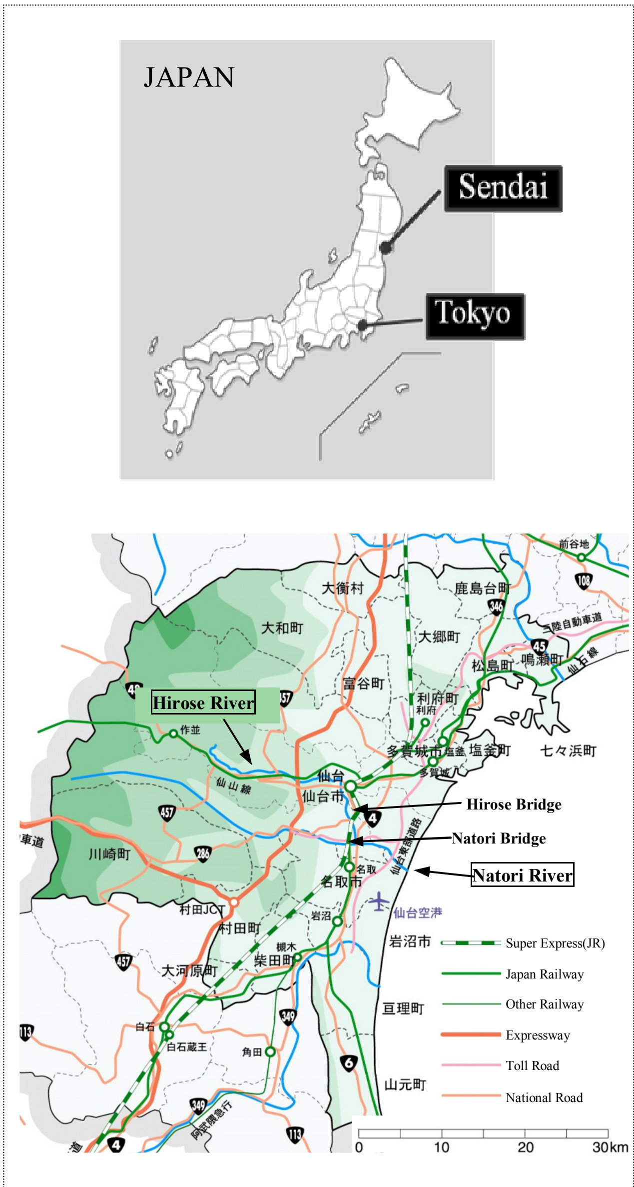


Figure 2: Sendai Metropolitan Area

of two models. The first is a water cycle model that explains the flow of rivers and subterranean water, sewers, and water used in industry and agriculture. The second is a material cycle model that explains the occurrence and behavior of water pollutants.

Because the previously-published Model System targeted the Sendai metropolitan area, this study targets the Natori and Hirose River areas in Sendai metropolitan area (population approx. 1.5 million) (Figure 2).

In metropolitan areas that conduct person trip surveys to understand the transportation activities of their residents, it is possible to obtain data for constructing an activity model. Person trip surveys are conducted in the major cities of most countries, making it possible to apply this Model System in other metropolitan areas.

3.2 Water Cycle Model

The water cycle model takes as an input value the output value of the above activity model, and predicts the water cycle. The transportation and land use models, which form

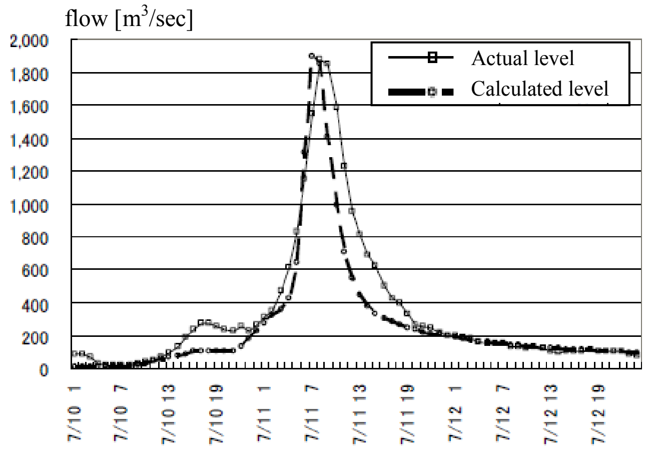


Figure 3: Measured and Predicted Values 1 (Natori Bridge)

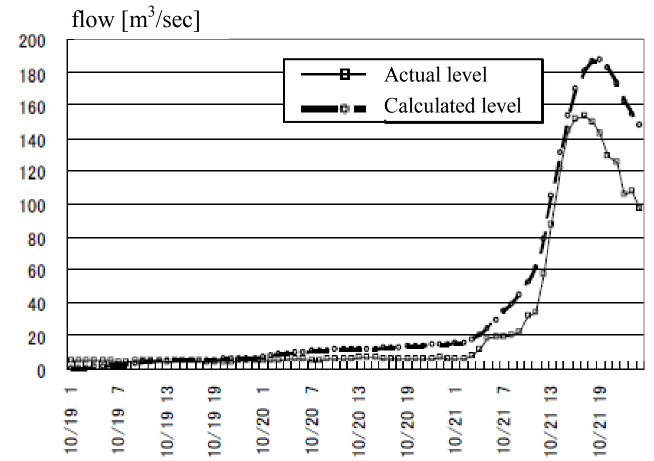


Figure 4: Measured and Predicted Values 2 (Natori Bridge)

the activity model, work together to predict the demand and population distribution, and further predict the land use in 1km mesh units from the population distribution. Transportation and land use models are used in city planning and transportation planning, but a model that links with a water cycle model generally did not exist until now. This Model System is advantageous to other model systems for its ability to assess city planning from the perspective of a water cycle.

The water cycle model is formed from a natural water cycle model and a river channel model.

The natural water cycle model is a multi-level tank modelthat expresses each watershed mesh as tanks made of three zones. Rain that falls on the ground flows as surface water when the ground's absorption capacity is exceeded. Water that is absorbed into the center tank accumulates in the soil. When the retention level exceeds the soil's thickness,the excess flows along the ground as surface water. This surface water flows into river channels hourly.

The river channel model is a distributed flow model using the kinematic wave method. The calculated time interval is one hour, and the spatial unit is 1km by 1km. The model creates a pseudo-channel network that connects the centers of the meshes, and calculates the water flow by conducting a follow calculation for the contents from each mesh that pass through the pseudo-channel network to the watershed exit. The follow calculation uses Manning's law.

We tested the reproducibility of the water cycle model using data observed for rainfall and water flow volume during the two periods of July 10th to 12th and October 19th to 22nd in 2005. Figures 3 and 4 compare actual and calculated levels at Natori Bridge taken over time. The predicted levels during the peak flow for the October 19th to 22nd period are a little low, but the results are quite positive (Figure 4).

3.3 Material Cycle Model

The material cycle model takes as an input value the population distribution produced from the above land use model to predict the material cycle model. Until now, an activity model that links with a material cycle model generally did not exist. This Model System is advantageous to other model systems for its ability to assess city planning from the perspective of a material cycle model.

This model describes the method for estimating the amount of water pollutants. We estimated the discharge load from households using the discharge load unit per person. For regions with sewage treatment facilities, we considered the discharge to have been treated. We estimated the discharge load from factories using the discharge load unit per item manufactured. We assumed that discharge from factories that are separated from rivers was treated in sewage treatment facilities. We estimated the discharge load from livestock using the discharge load per animal, controllingfor the discharge rate for each species. For the amount of treated human waste, we referred to materials from Miyagi Prefecture. For discharge loads from mountains, forests, fields, and urban areas, we estimated the amount using the discharge load unit per area of land use.

To estimate the displacement of water pollutants, we applied the tank model and conducted an estimation using a simultaneous differential equation. We solved the equation by simplifying it using a computer program that calculates sequential equations. The tank model of this research constructs three vertical zones (surface flow tank, central flow tank, and underground water tank) in 1km mesh in the target area. Together, they make up the river channel model. During clear weather, the change in BOD concentration is measured from the surface flow only. During rainy weather, the change in BOD concentration is measured from the surface and central flow, with overflow from the central flow tank flowing into the underground water tank.

For the water quality follow calculation, we applied the kinematic wave model.Because the calculated amount of accumulated material at river intersections becomes massive, we simplified it.

We tested the reproducibility of the material cycle model using BOD concentration comparisons from Natori Bridge, where the volume of water flow is easily reproducible. The assessment period was October 19th to 22nd in 2005.

The lowest estimated value of BOD concentration during the October 19th to 22nd period in 2005 was 0.67mg/l, and the highest estimated value was 1.2mg/l. The actual measured data is limited, but the range in an average year is between 0.6 and 1.6mg/l, and the actual data for a period close to the one estimated is 1.4mg/l for October 16, and 0.8mg/l for November 6th, so the results are quite positive.

Table 1: Measures Targeted for Assessment

	Case	Policy Contents
No Measures	Case 0: No Measures Taken	• No Land Use or Aquatic Environment Measures
Land Use Measures	Case 1: Urban Residence	• Reducing Burden on Urban Residence
	Case 2: Urban Sub-Center	• Proximity of Work and Residence Through Urban Sub-Center Planning
Aquatic Environ-mental Measures	Case 3: Sewer Planning	• Higher-Level Treatment of Upstream Runoff • Increase Treatment Capability for Runoff from Agricultural Settlements
	Case 4: Water Resource Planning	• 100% Cover Upstream Area With Forests • Increase Absorption Capacity Through Forest Care

Table 2: Population Distributions for Each Case

Distance from City Center	Case 0: No Measures Taken / Case 3: Sewer Planning / Case 4: Water Resource Planning [population]	Case 1: Urban Residence [Percent Change from Case 0]	Case 2 Urban Sub-Center [Percent Change from Case 0]
0 to 3 km	164,565	33.9%	0.3%
3 to 6 km	357,434	3.8%	-0.5%
6 to 9 km	306,459	-3.9%	-0.6%
9 to 12 km	255,530	-4.0%	0.6%
more than 12 km	485,012	-4.1%	0.3%
total	1,569,000	0.0%	0.0%

4. CASESTUDYOFTHESENDAI METROPOLITANAREA

4.1 Setting Up the Simulation Case

We conducted a simulation using the aquatic environment assessment model developed in this study. The measures targeted can generally be divided into land use measures and aquatic environment measures, where an assessment is possible by changing the input value in MERS. The measures tested are listed in Table 1.

Case 0 represents the best case for comparison where no land use or aquatic environmental measures are taken. We set up two cases of land use measures: an urban residence case, and an urban sub-center case.

Table 3: Results of the Flow Volume Assessment

Case	Flow Volume			
	Peak Flow Volume [m^3/s]		Minimal Flow Volume [m^3/s]	
	Natori Bridge	Hirose Bridge	Natori Bridge	Hirose Bridge
Case 0: No Measures Taken	160.9 (1.00)	59.6 (1.00)	5.77 (1.00)	4.39 (1.00)
Case 1: Urban Residence	127.5 (0.79)	59.5 (1.00)	5.69 (0.99)	4.34 (0.99)
Case 2: Urban Sub-Center	127.6 (0.79)	64.6 (1.08)	5.73 (0.99)	4.36 (0.99)
Case 3: Sewer Planning	160.9 (1.00)	59.6 (1.00)	5.77 (1.00)	4.39 (1.00)
Case 4: Water Resource Planning	160.9 (1.00)	45.2 (0.76)	5.77 (1.00)	4.55 (1.04)

note: the value in parenthesis is the percent change of the index value from Case 0.

The population distribution is the value predicted from entering the land use measures in MERS. Case 1 is the urban residence case, where urban residence is promoted byreducing the burden on urban residences within a 2km radius centered around Sendai Station.

Case 2 is the urban sub-center case, which creates four sub-centers - north, south, east, and west - at least nine kilometers from the city center, and promotes proximity of the home and workplace. The population distribution for each Case is listed in Table 2.

We also set up two cases for aquatic environmental measures. Case 3 is the sewer planning case, with higher-level treatment of upstream sewer runoff (improving the BOD removal rate from 90 percent to 98 percent). Case 4 is the water resource planning case, where we made the upstream region completely covered in forest, using the Sendai City plan as a reference, and increased the absorption capability (from 200mm/h to 260mm/h) by improving forest maintenance and care.

4.2 Assessment Using Flow Volume and Watershed Retention Capacity

The results of the comparison of the watershed retention capacity at peak and minimal river flow volumes for Natori and Hirose Bridges (see Figure 2 for bridge locations) are listed in Table 3.A large flow volume indicates a high retention capacity.

First, the results of the land use measures are listed. With Case 0 (no measures taken) as a basis of comparison, Case 1 (urban residence) shows no change at peak flow volume for Hirose Bridge, but for Natori Bridge shows an approximate 21 percent drop, revealing an improvement in watershed retention capacity through restrictions on suburban development. However, while Case 2 (urban

Table 4: Results of the Water Quality Assessment

Case	Water Quality Improvement Index (at minimal flow volume) BOD Concentration [mg/l]	
	Natori Bridge	Hirose Bridge
Case 0: No Measures Taken	1.17 (1.00)	2.01 (1.00)
Case 1: Urban Residence	1.17 (1.00)	2.02 (1.00)
Case 2: Urban Sub-Center	1.17 (1.00)	2.02 (1.00)
Case 3: Sewer Planning	1.09 (0.93)	1.94 (0.97)
Case 4: Water Resource Planning	1.17 (1.00)	1.96 (0.98)

note: the value in parenthesis is the percent change of the index value from Case 0

sub-center) shows a peak flow volume reduction of approximately 21 percent for Natori Bridge, it shows an increase of approximately 8 percent for Hirose Bridge, revealing a reduction in retention capacity for the Hirose River area. This is due to the fact that one of the urban sub-centers is located in the Hirose River and up-river area,and development in this area reduces water retention capacity.

Next, the results of the aquatic environmental measures are listed. Case 3 (sewer planning) shows no change in flow volume when compared to Case 0 (no measures taken). However, while Case 4 (water resource planning) shows no change at Natori Bridge, for Hirose Bridge it shows a reduction of approximately 24 percent at peak flow volume, and an increase of approximately 4 percent at minimal flow volume, thus showing an overall increase in water retention capacity for the Hirose River area.

4.3 Assessment Using the Water Quality Improvement Factor

To evaluate the water quality improvement factor, we compared BOD concentration levels for Natori and Hirose Bridges when the river flow volume had settled to minimal levels (Table 4).

Regarding land use measures, when compared to Case 0 (no measures taken), both Case 1 (urban residence) and Case 2 (urban sub-center) showed no change in BOD concentration, and no effect from land use measures.

Aquatic environmental measures, however, showed an increase in the water quality improvement factor, with Case 3 (sewer planning) showing a decrease in BOD concentration of approximately 7 percent for Natori Bridge, and approximately 3 percent for Hirose Bridge, when compared to Case 0 (no measures taken). In addition, Case 4 (water resource planning) showed a decrease of approximately 2 percent in BOD concentration for Hirose Bridge. This is likely due to an increase in minimal-level flow volume.

The results of the above case study of the Sendai metropolitan area show that it is possible to increase watershed retention capacity and raise the water quality improvement factor by changing land use to an urban residence model for city structure and by implementing water resource planning. Furthermore, in addition to these measures, it is possible to raise the water quality improvement factor by implementing sewer planning measures.

5. CONCLUSION

5.1 Results of this Study

1) This study integrated into our previously-published package model for comprehensive environmental assessment an aquatic environment assessment model that makes it possible to assess watershed retention capacity and the water quality improvement factor. The aquatic environment assessment model links with land use and transportation models to evaluate river flow volume and water quality.
2) This study used the aquatic environment assessment model to conduct a case-study of land use measures and aquatic environmental measures in the Sendai metropolitan area. It made clear that an urban residence model for land use is good for the aquatic environment by restricting development, that water resource planning is effective for increasing watershed retention capacity, and that sewer planning measures are effective for increasing the water quality improvement factor.

5.2 Subjects for Next Study

1) By improving the aquatic environment assessment model developed in this study, it will be possible to quantitatively evaluate the impact of typhoons and regional rainstorms, the damage from which is expected to be immense due to global warming. We hope to use the MERS integrated model system to comprehensively evaluate urban environments, and to use it in city policies that include disaster prevention planning.
2) We also hope to use this model system for urban recovery planning following the Great East Japan Earthquake and Tsunami of March 11, 2011.

6. ACKNOWLEDGMENT

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Pertinent discussion including authors' closure, if any, will be published in the March 2013 if the discussion is received by Sept. 2012.**Corresponding Author: Tetsuo Morita**